

FORMATION FLYING TECHNOLOGIES AND APPROACH FOR THE NASA ST3 MISSION

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ABSTRACT - *Spaceborne optical interferometry has been identified as a critical technology for many of NASA's 21st century science visions. Included in the visions are interferometers that can probe the origins of stars and galaxies, and can ultimately study Earth-like planets around nearby stars. To accomplish this feat, precision separation of an interferometer's small collecting apertures by large baselines are required - hundreds of meters up to thousands of kilometers, along with multiple spacecraft formation flying to at least the centimeter level. An even finer control level is required, where the interferometer optical pathlengths over these distances must be controlled to the nanometer level. To date, the technologies have been demonstrated only in ground applications with baselines of order of a hundred meters; space operation will require a significant capability enhancement. This paper describes the Origins Space Technology 3 (ST3) mission concept with deep space precision formation flying technologies, as defined at the start of the project. The separated spacecraft mission is designed to provide a technology demonstration for deep space precision formations and very long baseline optical interferometry. The interferometer would be distributed over two small spacecraft: one spacecraft would serve as a collector, directing starlight toward a second one, called the Combiner, which would collect starlight separately and combine the light to perform the interferometric detection. The interferometer baselines would be variable, allowing spacecraft separations of 40 m to 1 km in a parabolic formation, and providing angular resolutions from 5 to 0.5 nanoradian (1 to 0.1 milliarcsec).*

1 - INTRODUCTION

Many scientific goals of the 21st century in the fields of astronomy and astrophysics require order-of-magnitude advancements in optical angular resolution. Angular resolution improves linearly with the diameter of filled-aperture telescopes, or in the case of interferometers, with the distance (baseline) between widely separated apertures. Interferometers with baselines of 100 meters are being implemented on the ground, offering fairly high (1 milliarcsec) resolution of compact astrophysical objects. Many more of these objects, however, are faint and can only be detected by taking advantage of the enormous increase in sensitivity afforded by space-based observation, beyond the turbulent and partially opaque atmosphere. Among the key scientific goals enabled by space-based optical interferometry are submilliarcsec measurement of stellar diameters, resolution of close and interacting binaries, detection of extra-solar planets, and precise measurement of galactic and cosmic distance scales.

Optical interferometers collect light at separated apertures and direct the light to a central combining location where the two light beams interfere. Fringes produced by the interference provide amplitude and phase information from which a synthesized image can be generated. Space-based optical interferometers can be implemented as single monolithic spacecraft, in which collecting apertures are separated by tens of meters; or implemented as separated spacecraft where baselines of hundreds, or even thousands, of meters enable measurement with very high (sub-milliarcsec) angular resolution. A separated spacecraft optical interferometer concept, referred to as the Space Technology 3 Mission (ST3), is a simplified interferometer that demonstrates enabling technologies while still retaining some science capabilities. It has been originally identified as the third NASA New Millennium deep space technology demonstration mission, and later transferred into the Origins Program. It is developed in preparation for the Terrestrial Planet Finder Mission, which is a five spacecraft infrared interferometer, along with other future exoplanet imaging and high resolution astrophysics formation flying missions.

2 - MISSION DESCRIPTION

The ST3 mission is focused on validating separated spacecraft interferometer methods in space using two free-flying spacecraft as apertures. ST3 will launch in March 2005 into an Earth-trailing heliocentric orbit. The technologies of deep space formation flying (FF) and separated spacecraft interferometry (SSI) will be demonstrated. Precision formation flying is required to maintain proper alignments and positions between the two spacecraft to enable use of the interferometer payload. ST3 will validate an ability to control two independent spacecraft so that their relative velocity is less than 10 microns/second, while maintaining separation distances from 40 up to 1000 m to a control accuracy of better than 9 cm. Once this capability is established, ST3 will measure fringe visibility amplitudes of

bright astrophysical objects (8th magnitude and brighter) in the visible, at 0.5 to 1 micron wavelengths, within the interferometer as a SSI technology demonstration mission.

Both ST3 spacecraft are stacked on a single Delta II launch vehicle to be delivered into space at the same time. The third-stage solid motor directly injects the two spacecraft into an Earth-trailing heliocentric orbit and then separates from the two spacecraft. The spacecraft are designed to remain attached together to allow complete bus and payload checkout in a Cluster Mode. This helps to ensure a safe formation acquisition immediately after the two spacecraft are separated. After formation acquisition, the spacecraft deploy their sunshades, and begin a month-long Formation Flying Experiment Period. This period is intended to allow the two spacecraft formation to perform FF checkout and experiments. This is followed by a 1.5-month Combiner Mode where only the Combiner instrument is used for interferometer checkout and experiments. The baseline mission is completed by executing a three-month Separated Spacecraft Interferometer Mode, where the full capabilities of both formation flying and interferometry are orchestrated to perform observations.

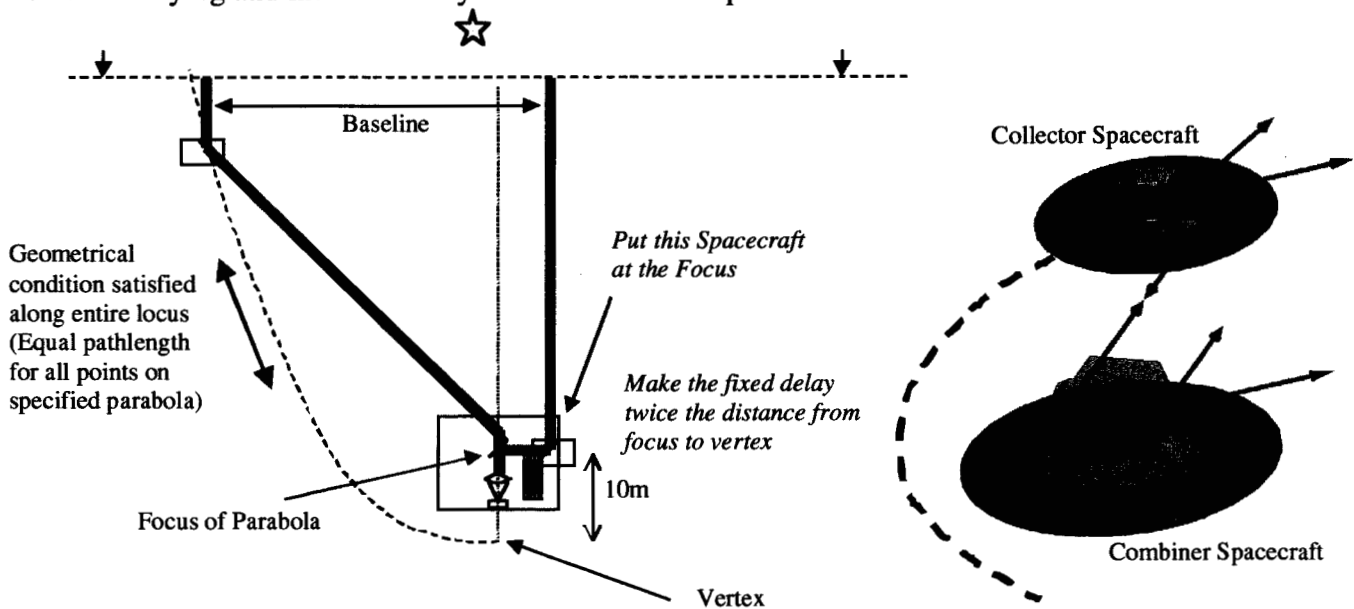


Figure 1. ST3 parabolic formation.

2.1 - Science Capabilities

Compared to current and near future ground-based optical interferometers, ST3 will have longer baselines. In addition, a more accurate calibration of visibility amplitudes will be possible, due to the lack of atmospheric coherence losses. ST3 will therefore explore regions of new parameter space on the sky, even though it may be limited to some total number of observations. Below are some of the key science capabilities that may be possible with the mission.

One of the simpler measurements involves Wolf Rayet stars. Some example targets are shown in Figure 2. These stars are hot and luminous, and have very strong stellar winds (i.e. they are losing mass

at a high rate). Current understanding of them is limited, although it is believed that they have evolved beyond the hydrogen burning (fusion) stage of stellar evolution. ST3 would allow the determination of the mass outflow in these objects for the first time, thus providing a quantitative test of their dynamics (size and shape).

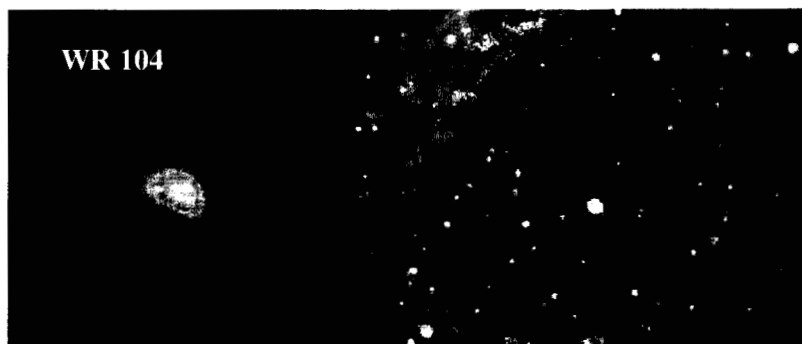


Figure 2. Examples of Wolf Rayet targets.

ST3 would also perform stellar structure investigations on cool stars. Cool stars play a major role in astrophysics; they define the largest stellar class, comprising our Sun as an average example. Most cool stars maintain magnetically confined atmospheres which give rise to particle acceleration and plasma heating. Investigations of the Sun in spatial and temporal detail have provided us with a considerable knowledge on energy release, structuring, and evolution of stellar atmospheres. However, the Sun represents a particular state of stellar evolution, for a particular stellar mass. Understanding the full range of phenomena related to stellar activity, mass loss, and evolution requires the study of solar-like phenomena in large samples of stars. ST3 is certain to increase our understanding by providing preliminary measurement of diameters of numerous cool stars

3.0 - FORMATION FLYING TECHNOLOGY DESCRIPTION

In addition to the requirements listed in Table 1, ST3 formation flying subsystem must also provide maneuvers to support interferometer observations. These maneuvers, as shown individually in Figure 3, can be combined into more involved sequences. The basic maneuvers include: 1) formation initialization from any position, 2) baseline orientation changes, to rotate the instrument about the line-of-sight, sweeping out a chord in the aperture plane; 3) change in formation size, to vary the angular resolution; and 4) retargeting the formation to point at other objects.

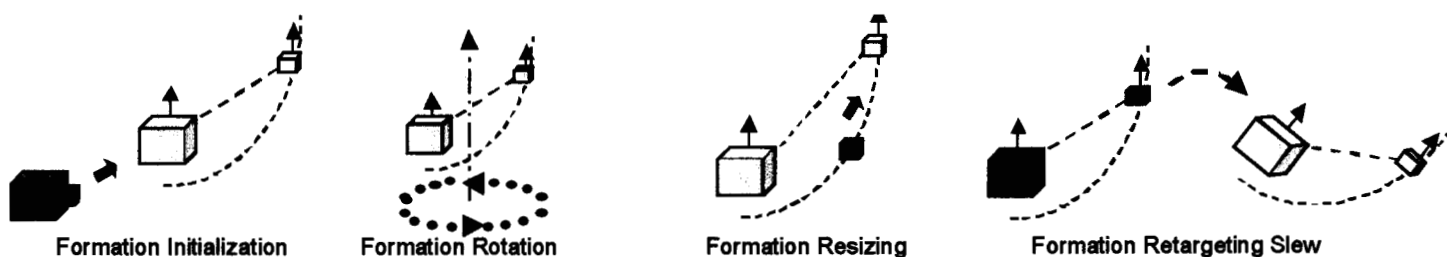


Figure 3. Formation flying maneuvers.

Requirement	Value
Time between thruster firings	Multiple 30 sec observation windows with 3 sec firing windows in between
Spacecraft nominal separation range	30 to 1000 m
Range control	+/- 9 cm
Range knowledge	2 cm (1 σ)
Range rate control	+/- 1 mm/sec acquisition, +/- 0.2 mm/sec observation
Bearing control	+/- 4 arcmin acquisition, +/- 0.73 arcmin observation
Bearing knowledge	1 arcmin (1 σ)
Bearing rate control	+/- 0.1 arcsec/sec
Combiner attitude control	+/- 3 arcmin
Combiner attitude knowledge	0.14 arcmin (1 σ)
Collector attitude control	+/- 3 arcmin
Collector attitude knowledge	0.17 arcmin (1 σ)

Table 1. Primary ST3 formation flying requirements.

The principal technologies required to perform deep space precision formation flying for ST3 optical interferometry include formation sensing, communications, estimation and control and spacecraft actuation.

3.1 - Formation Flying Sensing

A revolutionary improvement in accuracy and performance for relative spacecraft positioning is required for ST3. Traditional ground-based systems are orders of magnitude too noisy and too expensive to provide the required information. The Autonomous Formation Flying Sensor (AFF) addresses the aforementioned, and even more, key challenges presented by ST3. The AFF enables two spacecraft in deep space to autonomously maintain a precise relative position. Furthermore, it has a general architecture enabling it to be used on a variety of different missions, such as formations with higher number of spacecraft, along with rendezvous and docking, without significant re-engineering.

The AFF uses GPS-like (Global Positioning Satellite) signaling among multi-channel transceivers on both spacecraft. However, no near-Earth GPS signals are used for ST3. Each spacecraft hosts an AFF unit that can transmit as well as receive. Each spacecraft transmits a carrier and pseudorange signal to another via two omni antennas providing 4π steradian transmission coverage. Multiple patch receive antennas on each spacecraft allow 4π steradian angular coverage as well as determination of bearing angles and range.

Each AFF would determine precise bearing angles by tracking the relative carrier phase received from three antennas mounted on a front face of the spacecraft. An omni antenna on the back face of the spacecraft would provide information for the spacecraft to turn and face with the front tracking antennas. The relative range of another spacecraft can be precisely determined from the pseudorange

data, up to a maximum range of 10 km. The accuracy for the AFF is better than ± 2 cm in range and ± 1 arcminute in bearing angle, consistent with the ST3 formation flying knowledge requirements.

The concept for formation initialization consists of two types of metrology systems used in successive field of view (FOV) versus accuracy levels. The AFF would be used for coarse acquisition, providing centimeter and arcminute levels of spacecraft position accuracies, in a spherical coordinate system. An interferometer laser metrology system would then be used to provide fine bearing angle information (arcsecond level) between spacecraft during observation mode. This provides the ST3 formation flying system with a sufficient level of knowledge accuracy in order to provide 0.7 arcminute of formation bearing control.

Besides position sensing, attitude sensing is accomplished using coarse sun sensors, star trackers, and a fiber-optic rate sensor. The sensor suites on both spacecraft are identical to provide flexibility and reduce costs.

3.2 - Inter-spacecraft Communications

An UHF communications package has been selected for communications between the spacecraft. This device is to be shared between FF and the interferometer for data passing and commanding. This system is required to support 200 kbps with a 29 dB margin at separations of under 1 km, and support 8 bps at 3 db margin up to 200 km. The large operating range is for the case of anomalous behavior causing the spacecraft to drift beyond the 1 km specification. With 500 hertz interferometer metrology closed loop bandwidth, a <1 msec latency is require from the UHF device, assuming half of the requirement is levied against data transport by computers on both spacecraft.

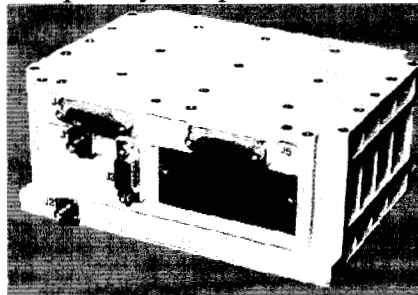


Figure 4. UHF inter-spacecraft communication transceiver.

3.3 - Formation Estimation and Control

The FF estimator and controller provide continuous six-degrees-of-freedom estimation and control capability during all phases of the ST3 mission. Both are baselined to reside on the Combiner spacecraft. Cooperative but centralized (master/slave) formation flying estimation and controls will be used for ST3 due to the small number of spacecraft and mission cost considerations. The master/slave control configuration simply assumes that a given (slave) spacecraft will perform formation adjustment

with respect to a second one (master). Formation stability can thus be maintained easily, avoiding situations such as duplicate spacecraft firings coincidentally.

For constellation of more than two spacecraft, research in the areas of dynamic interaction and the constellation stability is underway. Architectural issue of centralized vs. decentralized estimation and control become increasingly significant with larger number of spacecraft in a formation constellation. Issues related to symmetrical functionality with adaptive decentralized control architecture with its inherent robustness are being investigated.

An on-board guidance function on the Combiner will ensure collision avoidance during formation reconfiguration maneuvers. Additional spacecraft constraints, such as optical boresights, thermal constraints, and plume contamination, will also be included in the on-board maneuver design. The maneuver design will take into account criterion such as minimizing and balancing fuel usage between the two spacecraft.

The design approach for ST3 is to minimize the instrument to spacecraft interactions. The instrument provides the high bandwidth fine pointing and phasing control, with a dynamic range such that closed-loop spacecraft control is not needed. There is nominally no control actuation feedback between the interferometer internal control system and the spacecraft control system.

3.4 - Spacecraft Actuation

A propulsion trade was done to select the reaction control subsystem. Options included helium cold gas, nitrogen cold gas, pulsed plasma thrusters (PPT), field emission electric propulsion (FEEP), and hydrogen peroxide micro-propulsion. Drivers included the small impulse bits required (eliminated mono-prop and bi-prop), the short duration of mission operations, particulate and electro-magnetic contamination, and the tight mission cost constraints. Nitrogen cold gas was ultimately selected for ST3 to maximize the reliability to demonstrate precision formation flying and optical interferometry.

The spacecraft cold-gas propulsion system consists of the propellant storage tank(s), pressure regulator, twelve miniaturized 4.5-mN cold gas thrusters, latch valves, filter and service valves. The tanks are located to minimize CG shifts during on-orbit operations and enable simple balancing within the launch fairing. The thruster locations and orientations are selected to minimize the possibility of payload equipment contamination, while allowing the necessary attitude and translation maneuvers to be conducted.

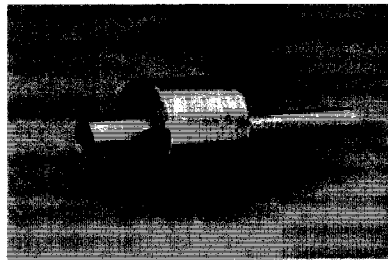


Figure 5. A 4.5 mN nitrogen cold gas thruster.

4.0 - CONCLUSION

The ST3 concept is a simplified separated spacecraft interferometer with the goal of technology demonstration to enable future applications of interferometer and other multiple spacecraft formations. Key technologies presented for precision deep space formation flying spacecraft include formation sensing, communications, estimation and controls and actuation of the formation.

ACKNOWLEDGMENTS

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REFERENCES

- [Deininger 00] W. Deininger, M. Noecker, D. Weimer, J. Eterno, C. Cleven, K. Patel, G. Blackwood, and L. Livesay, "Space Technology Three: Mission Overview and Spacecraft Concept Description," *International Academy of Astronautics*, IAA-L1107, Laurel, MD, May 2000.
- [Lay 99] O. Lay, G. Blackwood, S. Dubovitsky, P. Gorham, and R. Linfield, "Design of the ST3 Formation Flying Interferometer," *SPIE Optical Interferometer Conference*, Dana Point, CA, 1999.
- [Gorham 99] P. Gorham, W. Folkner, and G. Blackwood, "Enabling Concepts for a Dual Spacecraft Formation-Flying Optical Interferometer for NASA's ST3 Mission," *SPIE Optical Interferometer Conference*, Dana Point, CA, 1999.
- [Purcell 98] G. Purcell, D. Kuang, S. Lichten, S. C. Wu, and L. Young, "Autonomous Formation Flyer (AFF) Sensor Technology Development," AAS 98-062, Breckenridge, CO, 1998.
- [Wang 97] P. Wang, F. Hadaegh, and K. Lau, "Synchronized Formation Rotation and Attitude Control of Multiple Free-Flying Spacecraft," *AIAA GN&C Conference*, New Orleans, LA, August 1997.

- [Hadaegh 97] F. Hadaegh, K. Lau, and P. Wang, "Formation Flying Control of Multiple Spacecraft," *NASA URC Technical Conference*, Albuquerque, NM, February 1997.
- [Wang 96] P. Wang, and F. Hadaegh, "Coordination and Control of Multiple Micro-spacecraft Moving in Formation," *Journal of Astronautical Sciences*, Vol. 44, No. 3, July-Sept. 1996, pp. 315-355
- [Lau 96] K. Lau, S. Lichten, L. Young and B. Haines, "An Innovative Deep-space Application of GPS Technology for Formation Flying Spacecraft," *AIAA GN&C Conference*, San Diego, CA, AIAA Proceedings 96-3819, June 1996.



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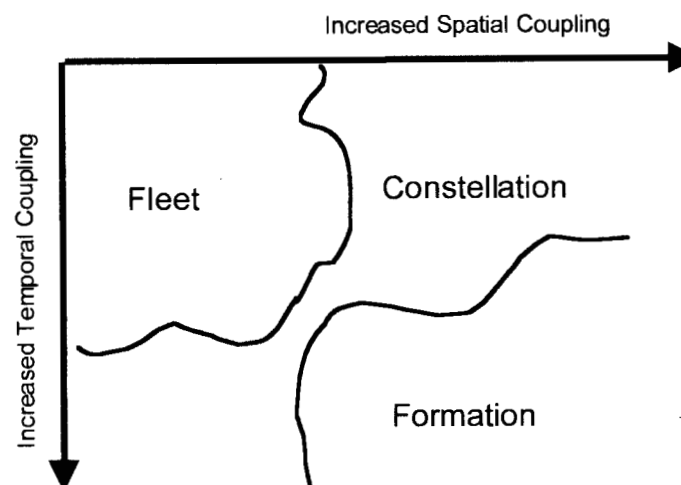
International Symposium on Spaceflight Dynamics
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Vocabulary for Multi-S/C Missions



	Geometric Pattern	Organization	Shared Sensing	Control Philosophy	Control Location
Fleet		Not organized spatially or temporally		Discrete S/C	Ground
Constellation		Partially organized spatially or temporally		Discrete S/C	Ground
Formation	Increased geometric structure ↓	Fully organized temporally and spatially	Increased sensor coupling ↓	Collective	Onboard





Spacecraft Fleet Example

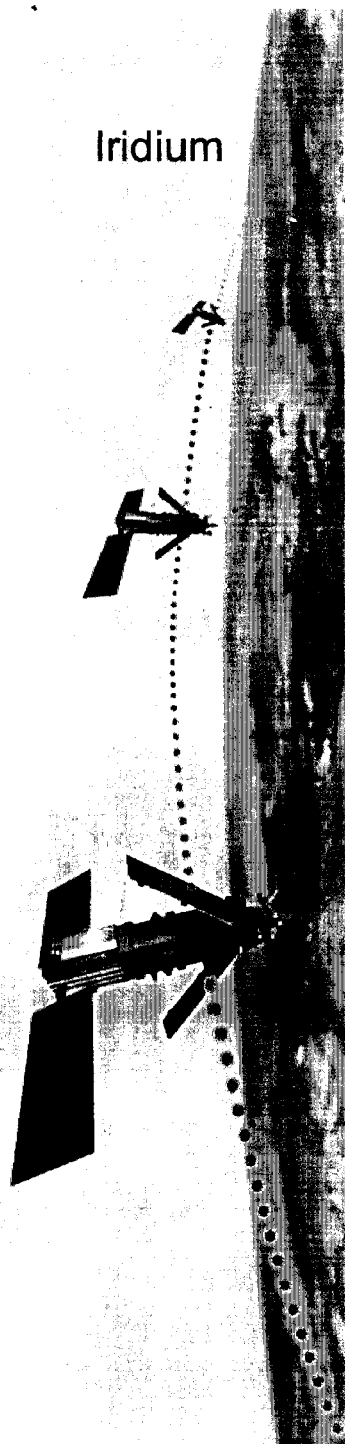


- Shuttle Fleet
- A collection of JPL deep space fleet that includes:
 - Rangers
 - Mariners
 - Surveyor
 - Viking
 - Voyagers
 - Magellan
 - Galileo
 - Mars Pathfinder
 - Cassini

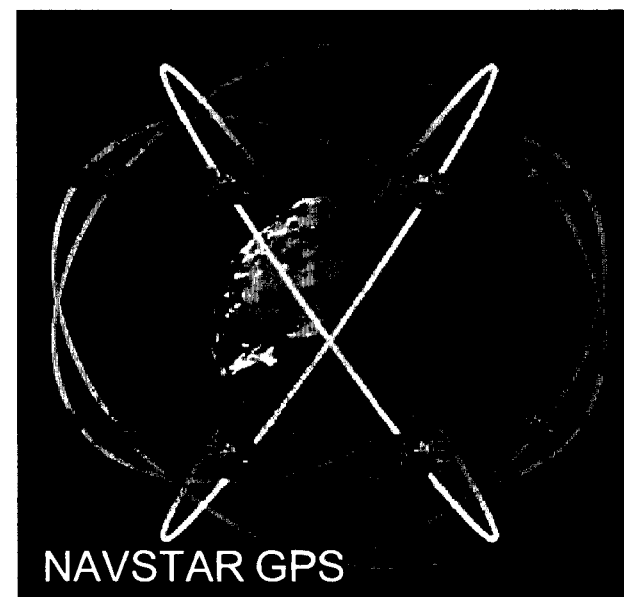


Constellation Examples

Iridium



- NAVSTAR Global Positioning System Satellites (24 satellites/6 planes)
- Constellation (formerly Aries) (48/4)
- ICO (formerly Inmarsat-P) (10/2)
- Teledesic (840/21)
- Globalstar (48/8)
- Odyssey (12/3)
- Iridium (66/6)
- Ellipso (10/2)

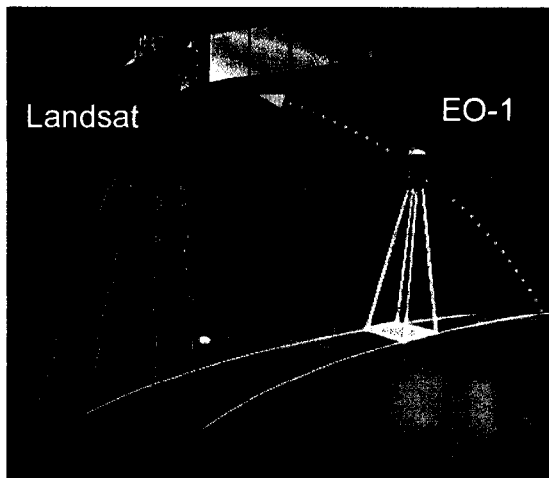




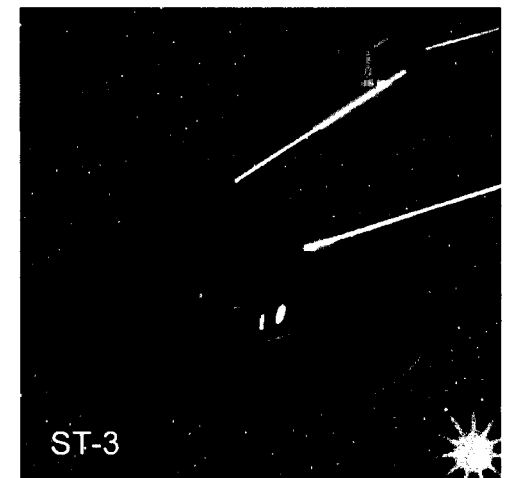
Formation Flying Classes & Examples



Class	Control Accuracy
Coarse	>1 km
Intermediate	1 m to 1 km
Fine	<1 m



- New Millennium Earth Orbiting Mission 1 (Coarse FF)
 - Accuracy measured in many kilometers
- New Millennium Space Technology 3 Mission (Precision FF)
 - Centimeter or better accuracy range





WHY FLY IN FORMATION?



Why Formation Flying?



- Enables science inquiries requiring large baselines
 - Practical limitations for single structure
 - Deployment, mass, size, other launch vehicle constraints
- Functional redundancy
 - Replenishment
- Smaller S/C may lead to potential cost savings



Future Formation Flying Missions

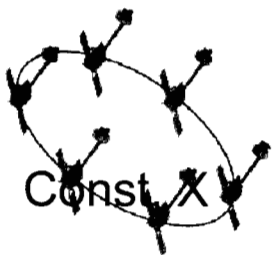


Deep Space

- '96 CLUSTER & '05 CLUSTER reflight
- '03 New Millennium ST-3 (in-dev)
- '04 Next Generation Constellation X-ray Mission (Constellation X)
- '08 Laser Interferometric Space Antenna (LISA)
- '10 Darwin Space Infrared Interferometer (Darwin)
- '10 Terrestrial Planet Finder (TPF)
- Planet Imager (TPI)
- MUSIC
- Astronomical Low Frequency Array (ALFA)
- MAXIM X-ray Interferometry Mission
- Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)
- Solar-Terrestrial Relations observatory (STEREO)
- Sagittarius/OMEGA
- Two-Wide Angle Imaging Neutral-Atom Spectrometers (TWINS)
- NIAC/Very Large Optics for the Study of Extrasolar Terrestrial Planets
- NIAC/Ultra-high Throughput X-ray Astronomy Observatory with a New Mission Architecture
- NIAC/Structureless Extremely Large Yet Very Lightweight Swarm Array Space Telescope
- Mars Exploration Fleet

Earth Orbiting

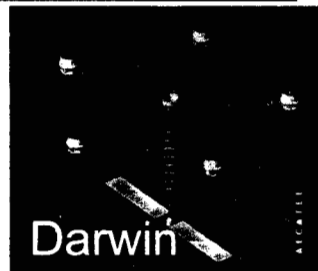
- '99 New Millennium EO-1 (in-dev)
- '01 Gravity Recovery & Climate Recovery (GRACE) (in-dev)
- '01 University Nanosat
- '02 Auroral Multiscale Mission (AMM)
- '02 ORION
- '02 Lightweight Synthetic Aperture Radar (LightSAR)
- '03 New Millennium ST-5 Constellation
- '03 Techsat 21
- '05 Magnetospheric Multiscale
- '07 Global Electrodynamics (GED)
- '08 Magnetospheric Constellation
- LEONARDO
- Orbiting Wide-angle Light-collectors (OWL)
- OPAL
- TOPSAT
- ATMS
- Global Precipitation Mission
- Soil Moisture and Ocean Salinity Observing Mission
- Time-dependent Gravity Field Mapping Mission
- Vegetation Recovery Mission
- Cold Land Processes Research Mission



Const X



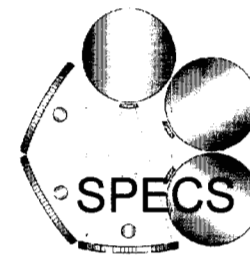
TPF



Darwin



AMM



SPECS



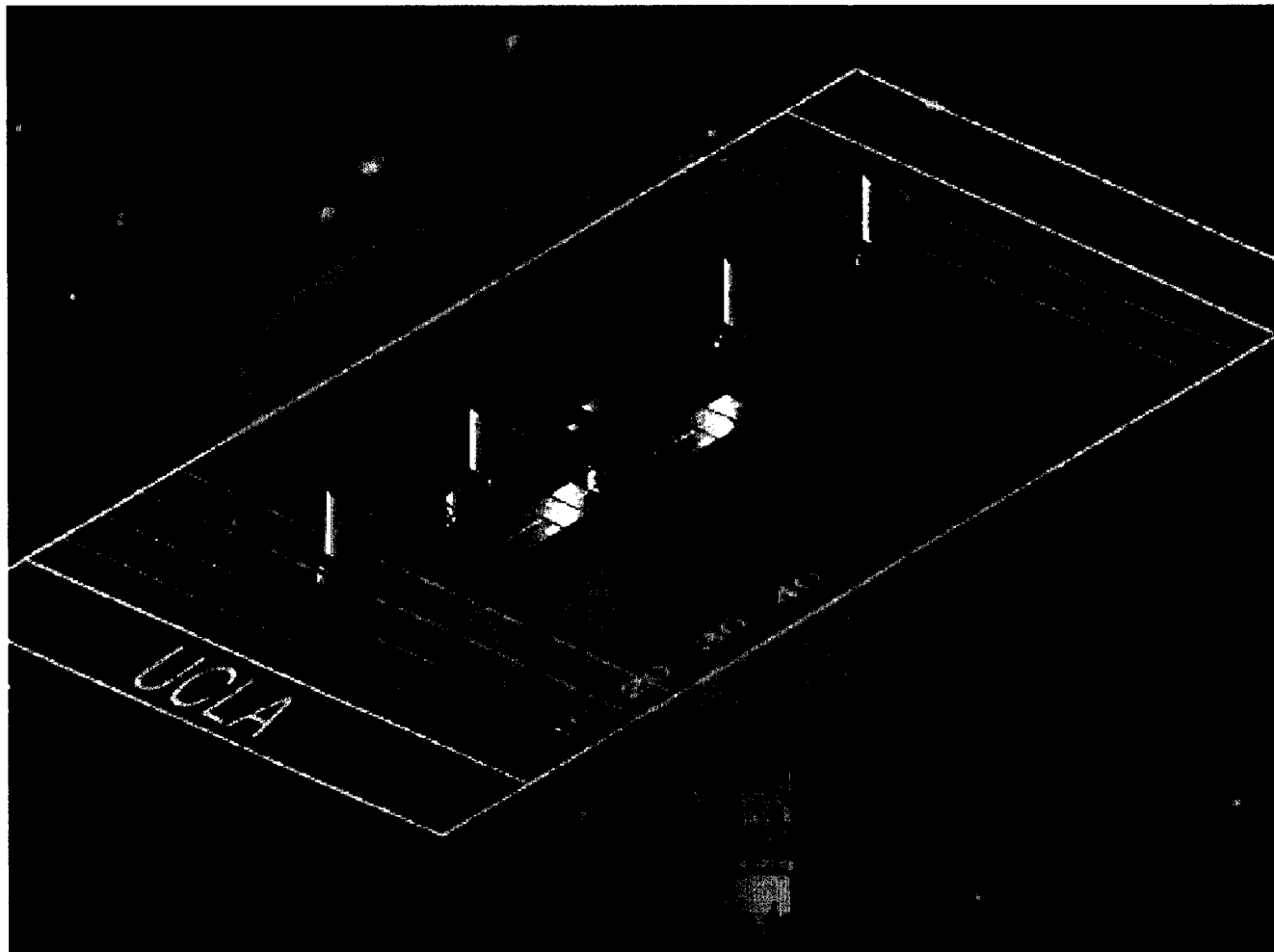
TechSat 21



Optical Stellar Interferometers

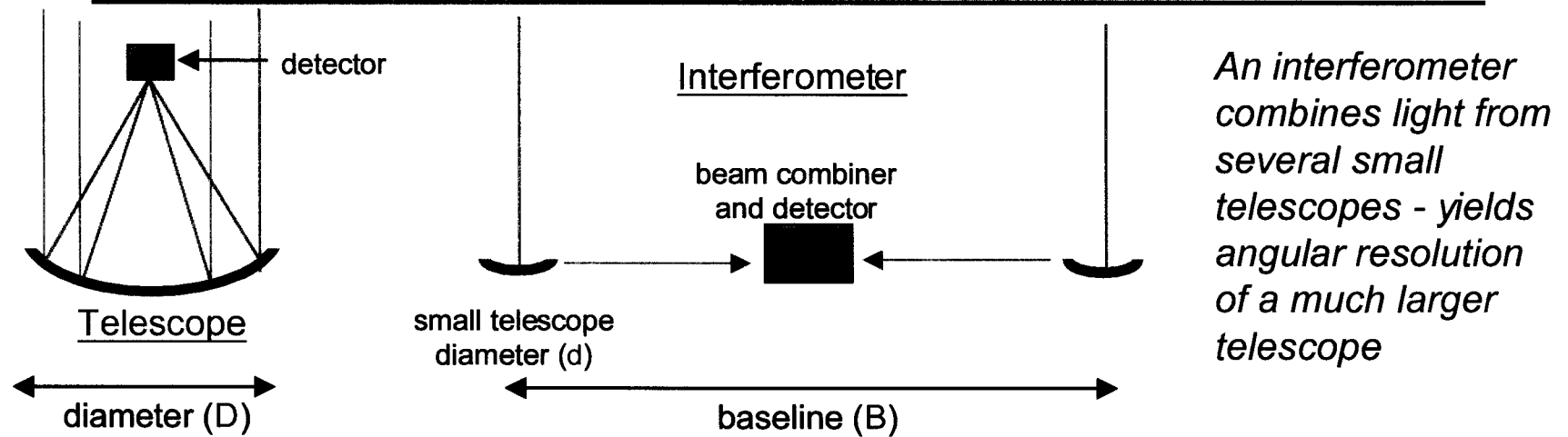



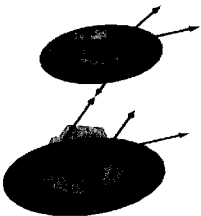
When telescopes the size of football fields are too expensive!





Telescopes vs. Interferometers



Examples	Imaging Resolution (ability to see fine details)	Field of View
 <p>D=2.4m $\lambda=0.5 \mu\text{m}$</p> <p>HST</p>	$\lambda/D = 40 \text{ marcsec}$	<p>2.7 arcmin</p> <p>(1600pixels*0.1asec/pixel) governed by detector size</p>
 <p>B=200m d=0.12m $\lambda=0.5\mu\text{m}$</p> <p>ST3</p>	$\lambda/B = 0.5 \text{ marcsec}$	<p>5-50 marcsec</p> <p>Set by $\lambda/(\text{sampling interval})$ of image plane</p>



SPACE TECHNOLOGY 3 MISSION



Space Technology 3

JPL

Mission Description:

1. Validate autonomous formation-flying system
 - Range control better than cm
 - Bearing control better than arcmin
 - Inter-spacecraft range up to 1 km
2. Validate technology for formation-flying optical interferometry performance goals:
 - Operational wavelength: 450-1000 nm
 - Baseline range: 40-200 m
 - Limiting magnitude: $m_v = 8$
3. March 2005 launch to a Heliocentric orbit

1. Delta-II launch to
heliocentric
Earth-trailing orbit

2. Combiner-mode
interferometer
observations

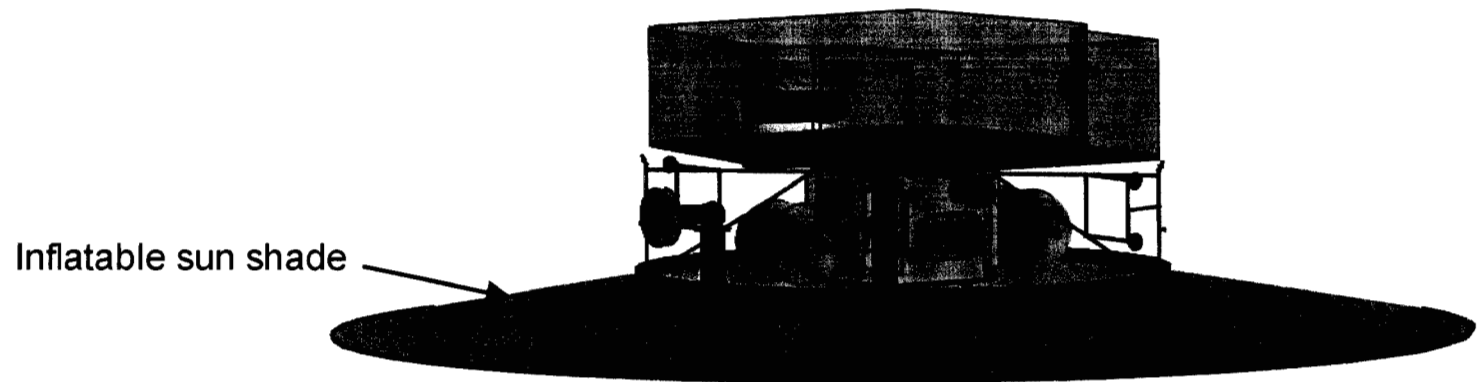
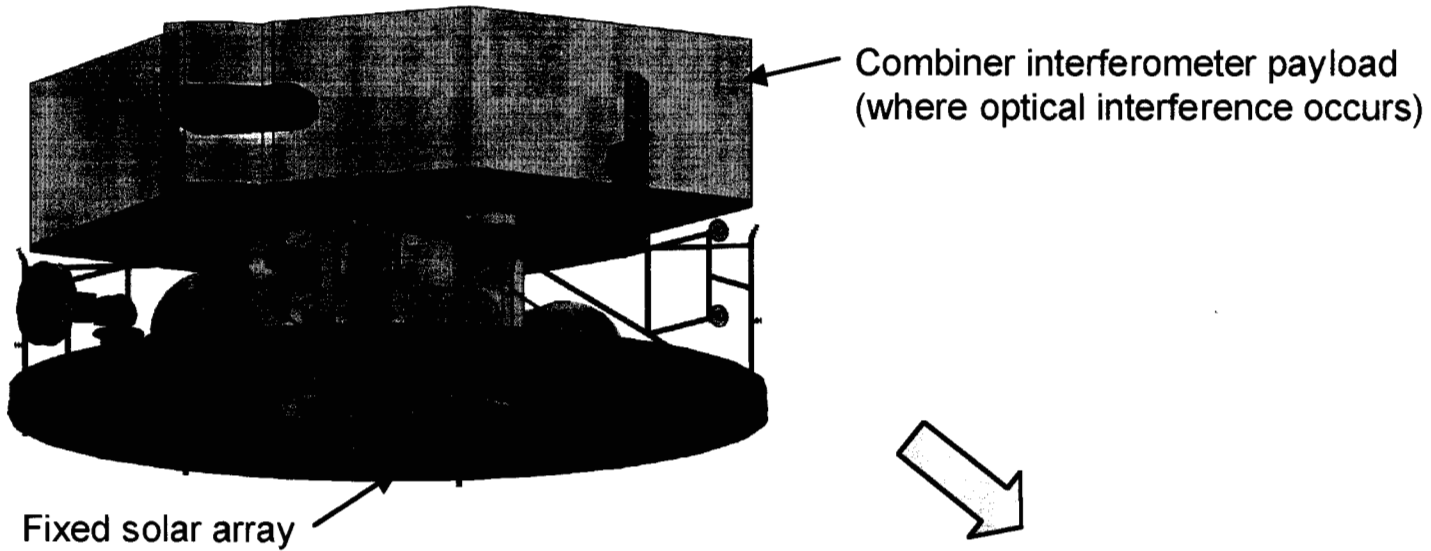
3. Spacecraft separate and
perform formation-flying
experiments 50 m to 1 km

4. Formation-flying
interferometer
observations



Combiner Spacecraft

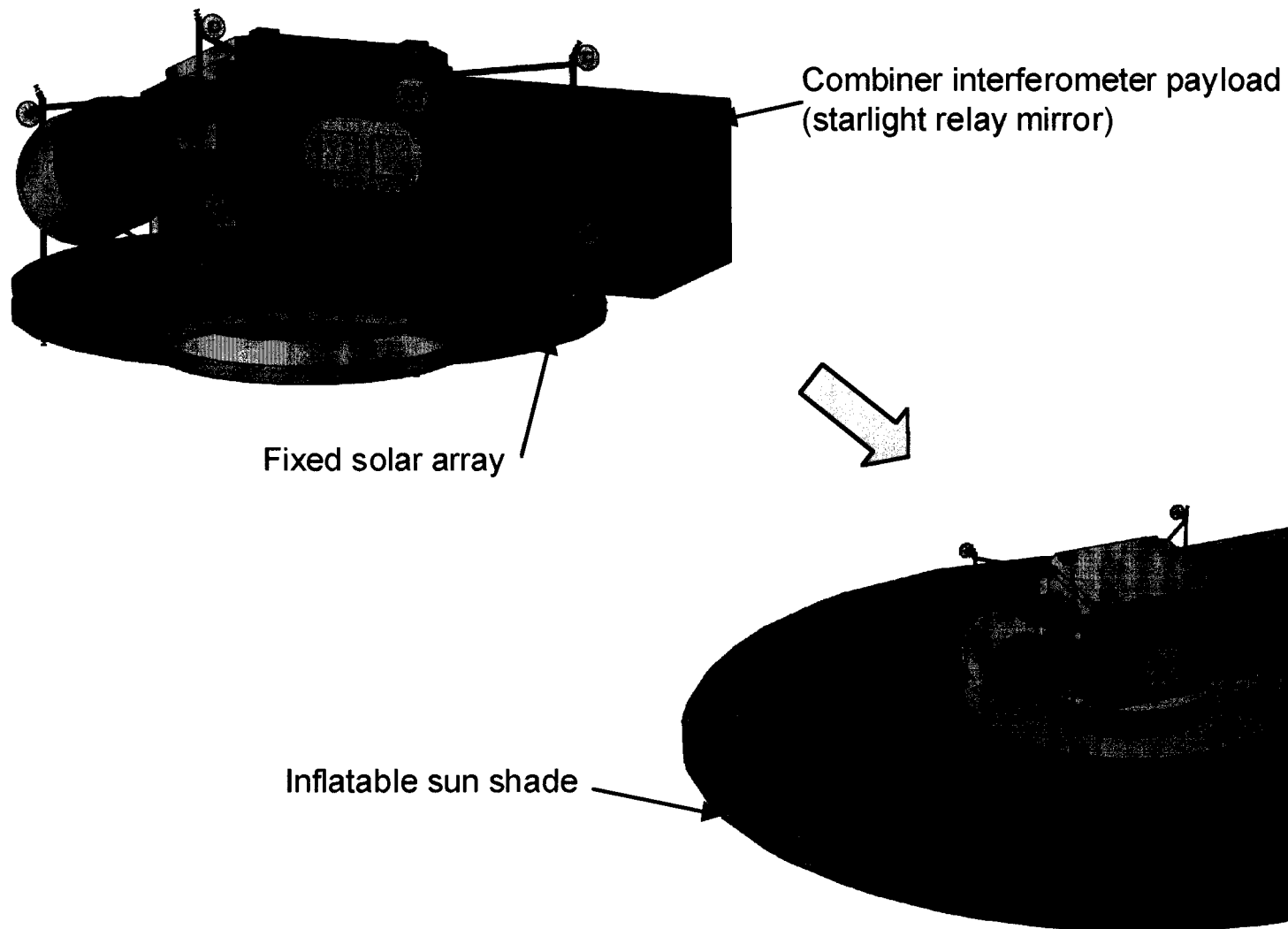
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Collector Spacecraft

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ST3 Science Capability

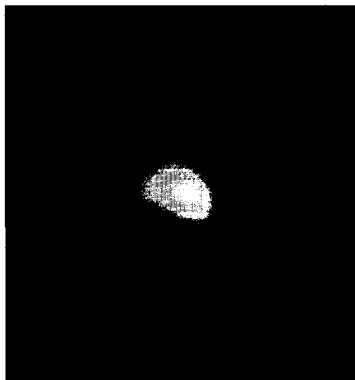
JPL

- Stellar structure
 - Diameters of cool stars
- Stellar evolution
 - Size & shape of Wolf-Rayet star outflow

WR 104 at 2.27 Microns

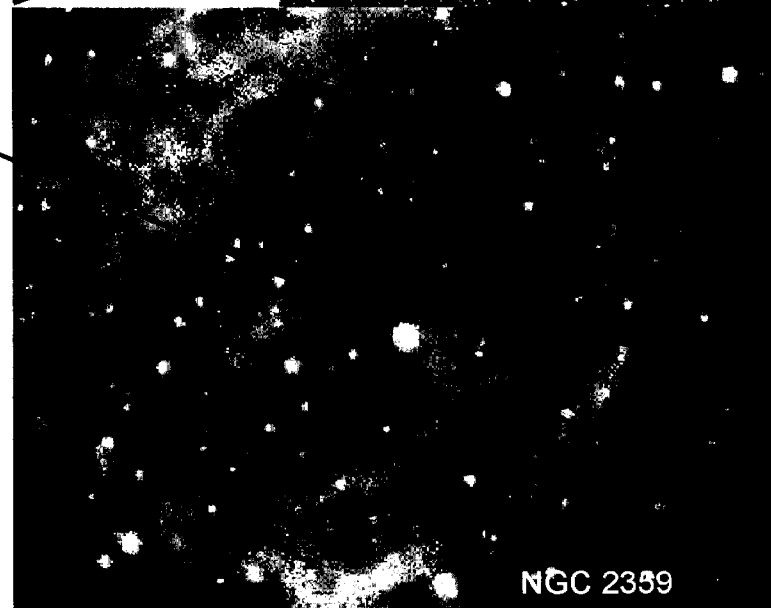
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1/10 ARCSEC

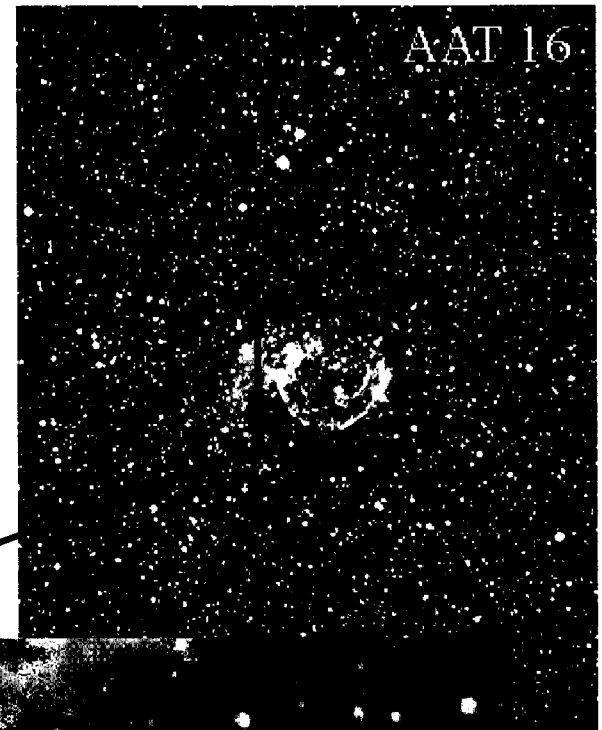


160 AU

WR



NGC 2359

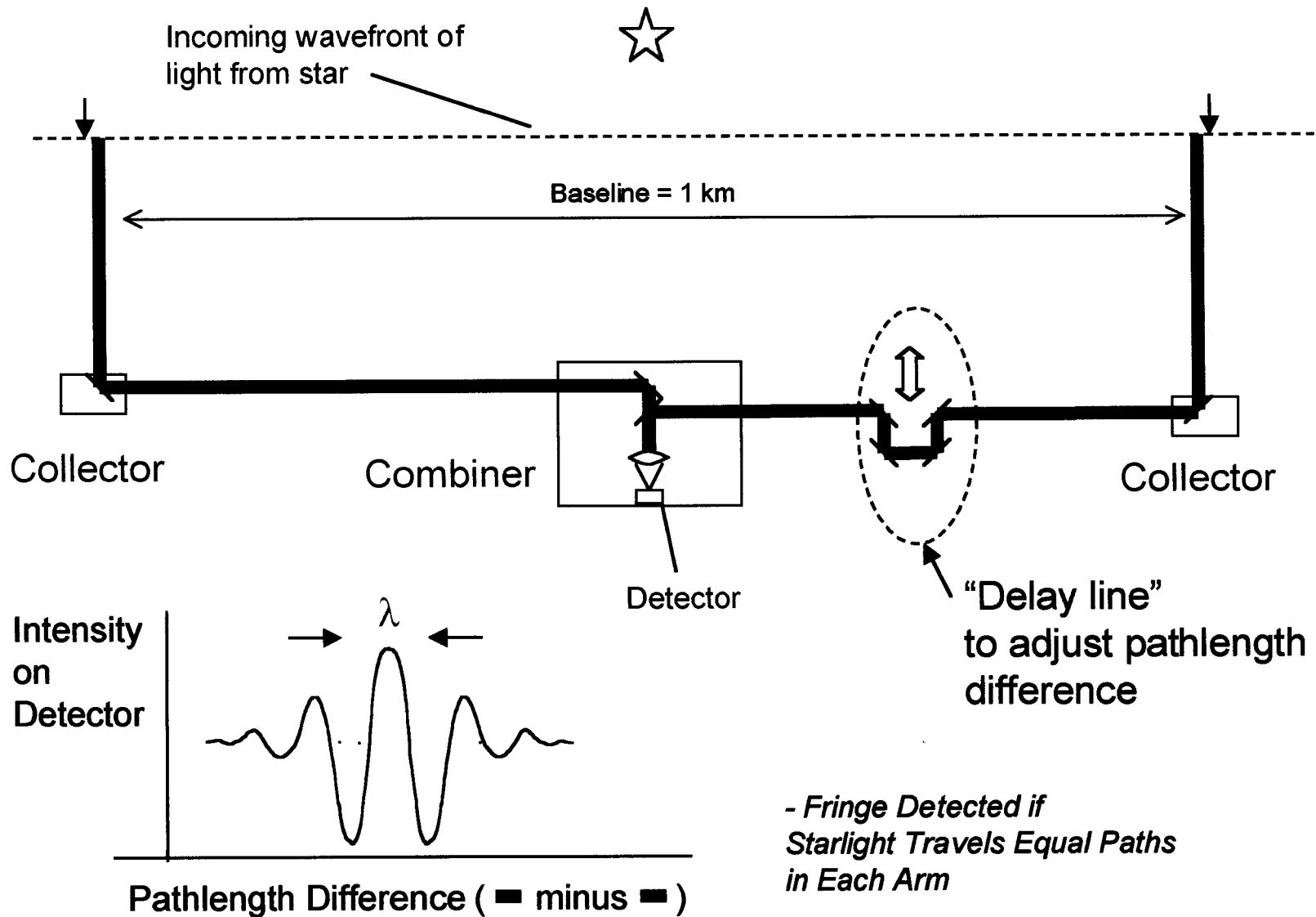


AAT 16



Interferometer Basics: Equal Pathlengths

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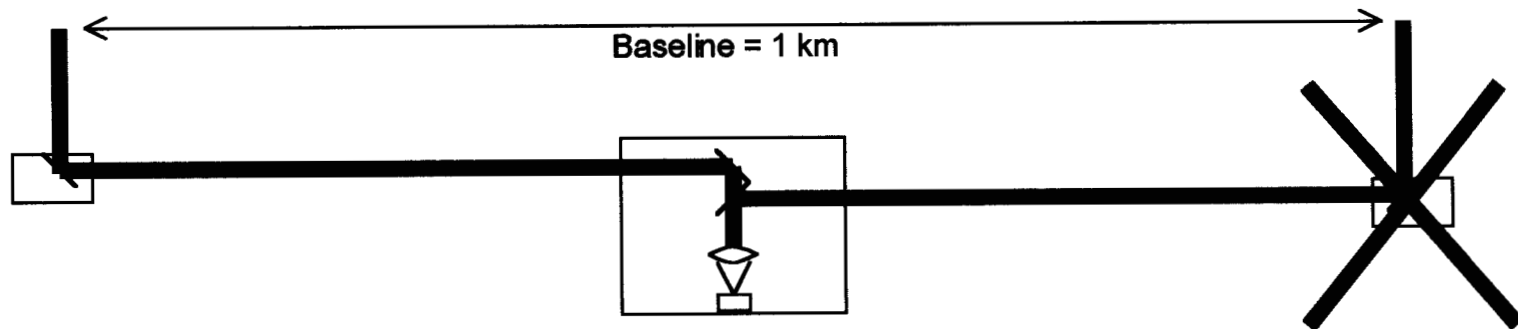




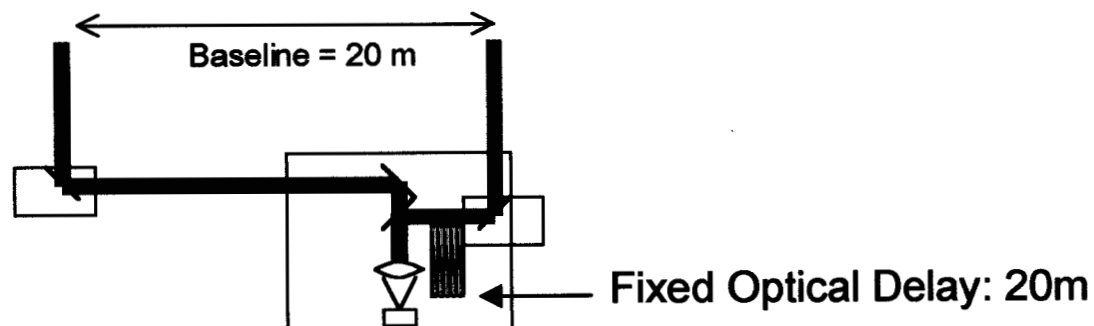
NASA Could Only Afford 2 Spacecraft



The original 3-spacecraft idea:



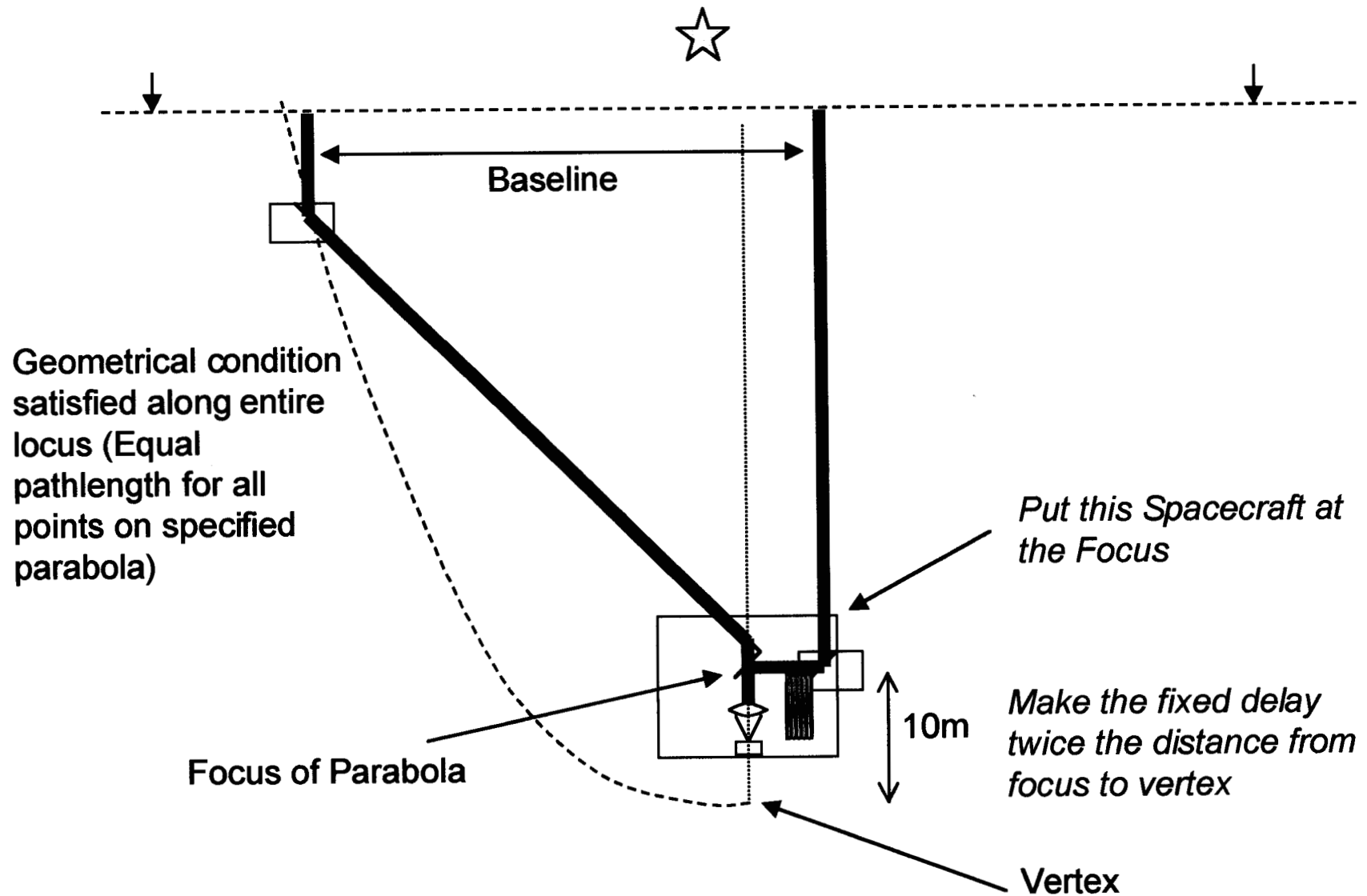
A 2-spacecraft version had problems:



*Problems -- Baseline is only ~20m!
Baseline not adjustable!*



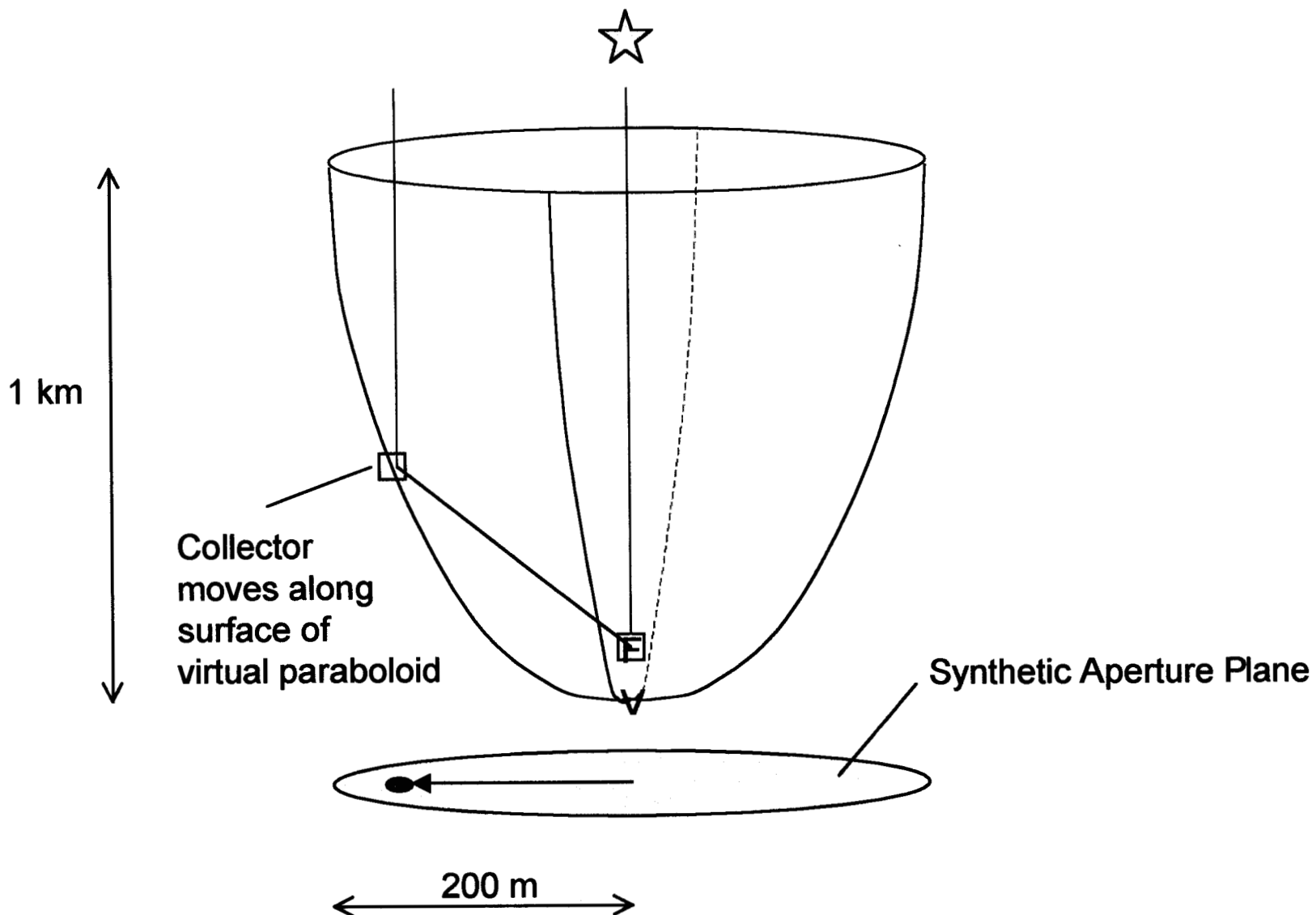
The Breakthrough: a Virtual Parabola





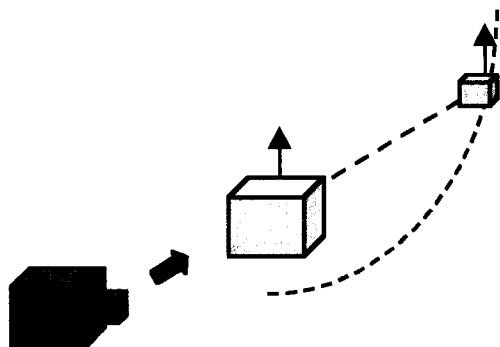
Aperture Plane Filling

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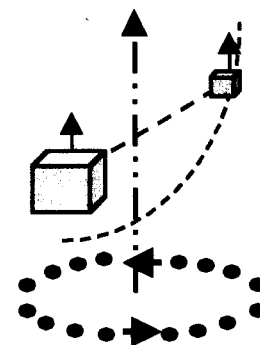




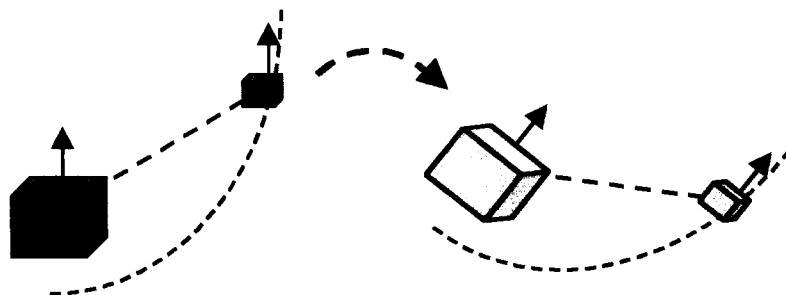
Formation Flying Maneuvers



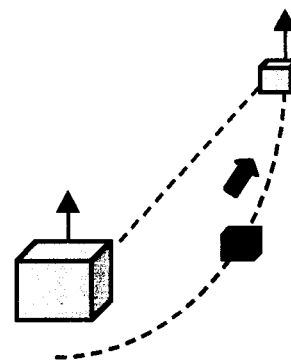
Formation Initialization



Formation Rotation



Formation Retargeting Slew



Formation Resizing

Formation observation maneuvers may combine above problems



ST3 FF General Requirements

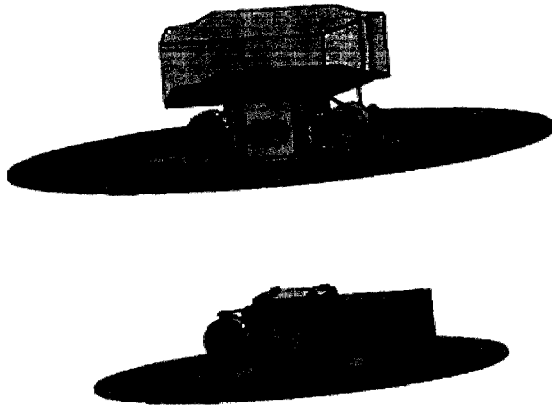


- Guidance & Control
 - 50m to 1km baselines
 - <1 cm relative range control
 - <1 arcminute relative bearing control
 - <0.1 mm/sec relative velocity measurements
 - Formation initialization and maintenance
 - Formation maneuvers
 - Low jitter
 - Long deadband times (~1000sec)
- Inter-spacecraft communications
 - ~100 kbits/sec for FF
 - ≥ 1 Mbits/sec, <1 msec latency for I/F
- Propulsion
 - Limited fuel mass
 - Perform large slews & translations
 - Provide small thrust for formation maintenance
- Autonomy
 - Cannot “joystick” from ground





FF Challenges & Technologies



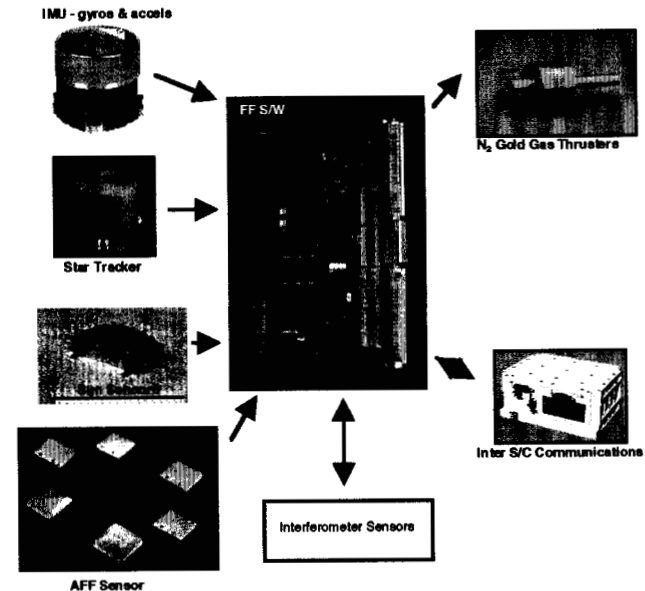
- Autonomous GN&C
 - Formation estimation & controls
- Formation sensing
 - Position, velocity & bearing
- Inter-spacecraft information coordination
- Propulsion
- Testing



Autonomous GN&C Technologies



- Autonomous formation flying controls
 - FF capabilities
 - Initialize from a small cluster
 - Initialize from random distributed positions
 - Coordinated pointing
 - Maintain formation during maneuvers
 - Controls architecture
 - Centralized
 - System-level fault isolation, recovery & prevention
 - Formation maneuvers
 - Dimensional changes
 - Efficient interferometer maneuvers
 - Center of mass of formation
 - Pivot around S/C with least fuel
 - Optimize for time and/or fuel
 - Collision avoidance
 - Launcher
 - Each other
 - Formation estimation
 - Formation sensor data fusion
 - Include interferometer sensors



ST3 Sensing & Actuation Architecture

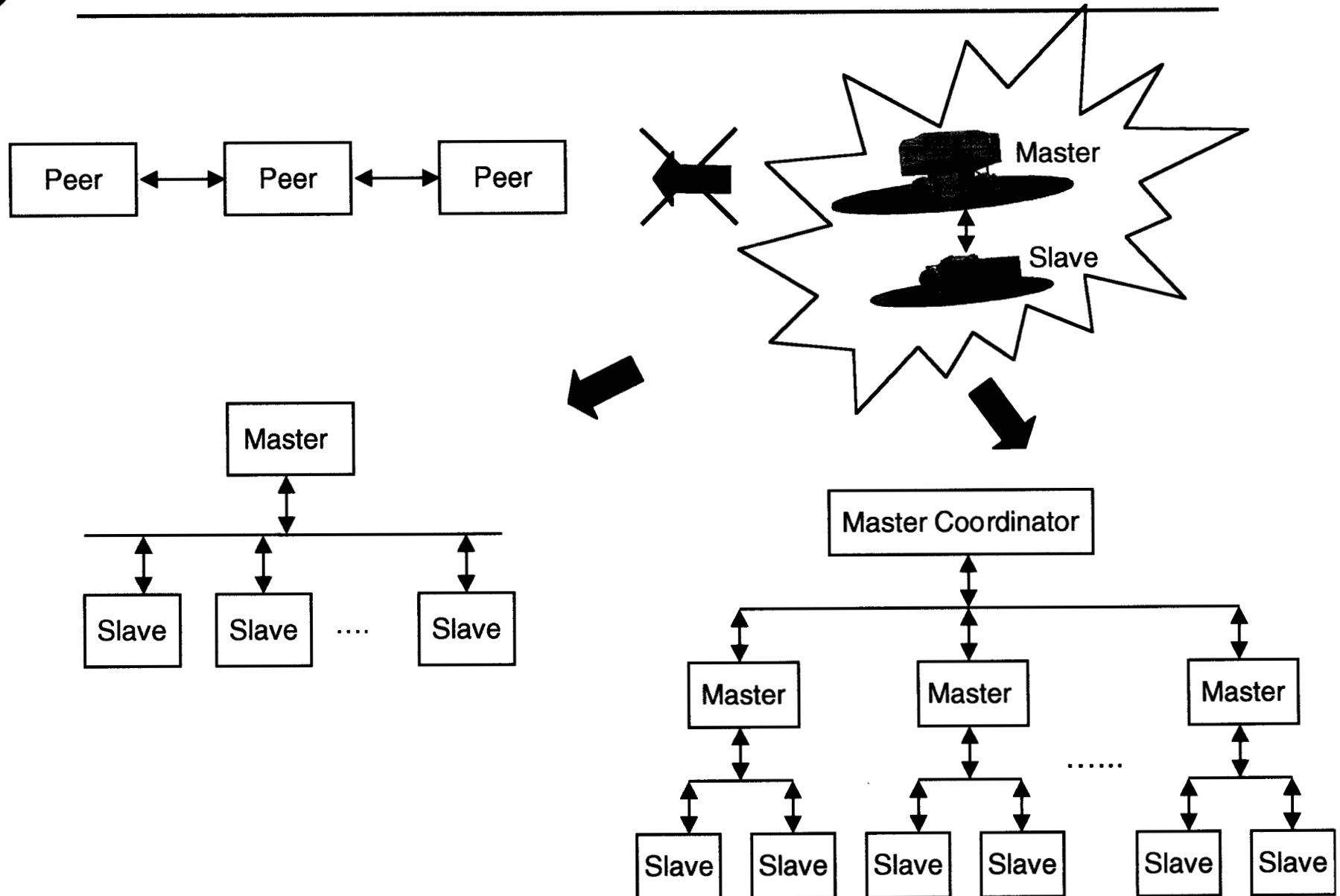


Formation Control Design Testbed (TPF configuration demonstration)



Scalability of Centralized Controls

JPL

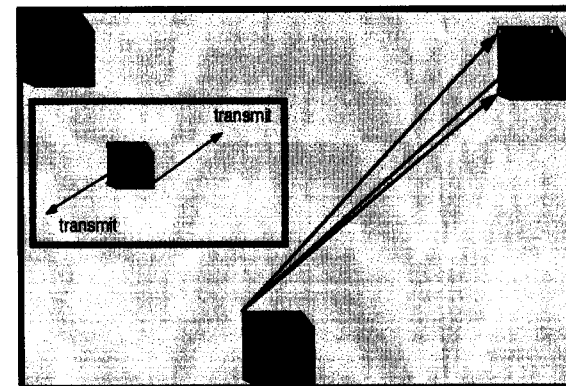




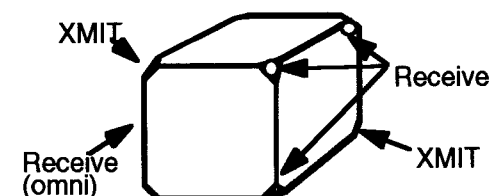
Formation Sensing Technology



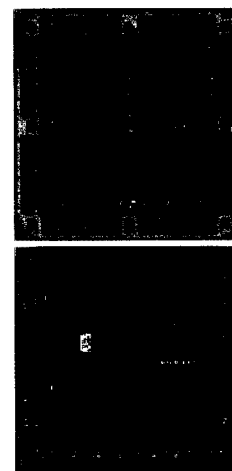
- Autonomous Formation Flying sensor (AFF)
 - GPS-like *transceiver*
 - Provide coarse formation range and bearing
 - I.e. position of 2nd S/C in spherical coordinate system
 - Does not use Earth's NAVSTAR GPS satellite signals for deep space
 - Transmits 2 *equivalent* NAVSTAR signals to another AFF
 - Transceiver generates ranging codes & carrier for transmission
 - No upper limit to a formation
 - Multiple antennas satisfy 4π steradian coverage requirement
 - 3 front receive antennas, 1 rear
 - 1 front and rear transmit antennas
 - Ka band signal, not L band
 - < 25 Wdc 2 kg total
 - 10 km range, 0.1 WRF



AFF Sensor



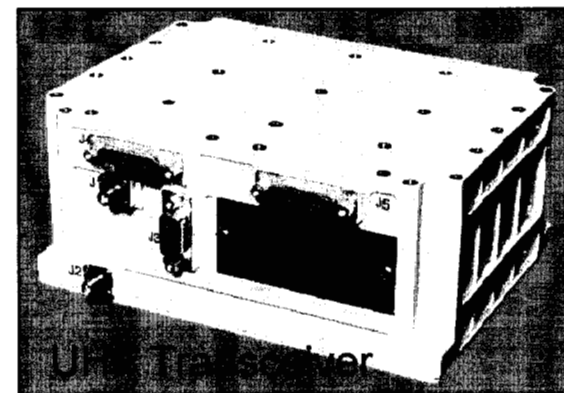
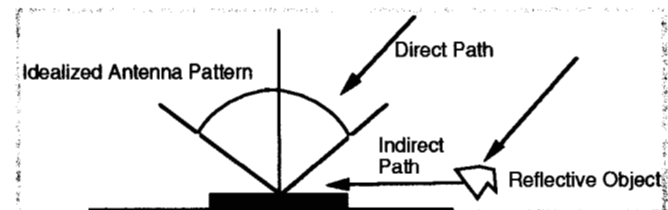
ST-3 Spacecraft
(shown with 4 receive antennas)



GPS Baseband Processor
Boards to be used for AFF



- RF Multipath
 - Accuracy degradation
 - Mitigation techniques
 - Calibration
 - Stealth techniques
 - Antenna design & placement
 - Other
 - Adaptive estimation & compensation - Seismic Deconvolution
- Inter-spacecraft network information coordination
 - High data rate inter-spacecraft communications
 - UHF transceivers
 - Other options
 - Radio ethernet
 - RF modem
 - AFF
 - Management of large parallel data sets
 - Latency, accuracy concerns

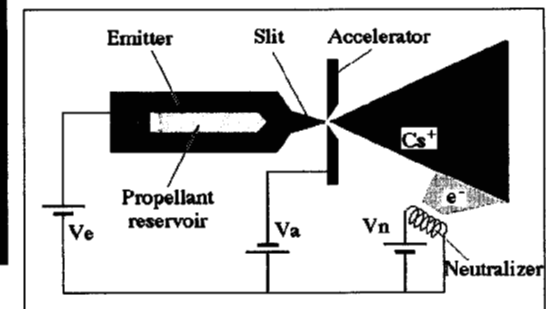
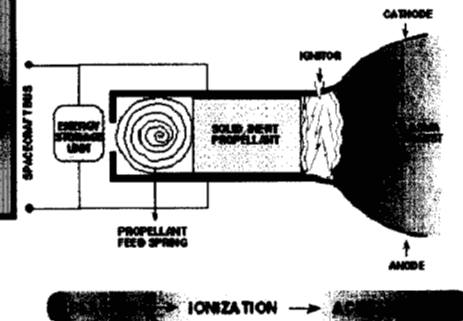
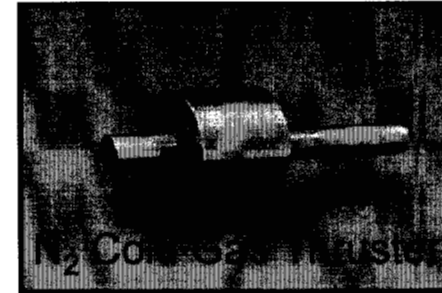




Propulsion Technologies

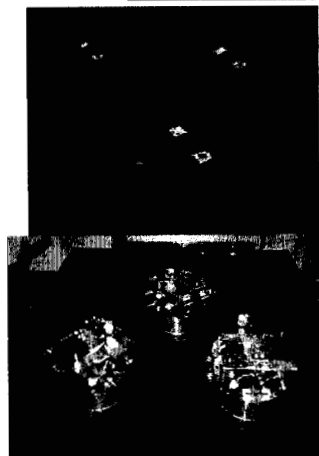


- Small thrusters
 - 12 per spacecraft
 - Cold gas (N_2) thrusters baselined
 - 4.5 mN
 - Low I_{sp} (60 sec)
 - Other options
 - Pulse Plasma Thrusters (PPT)
 - 700 μN per pulse, up to 6 Hz
 - High I_{sp}
 - Higher power
 - Contamination concerns
 - Field Electric Emission Propulsion (FEEP)
 - 1 μN to 2 mN thrust
 - Very high I_{sp}
 - Both create contamination concerns & require high power





Testbed Concepts



**3-DOF Mini
Indoor Testbeds**



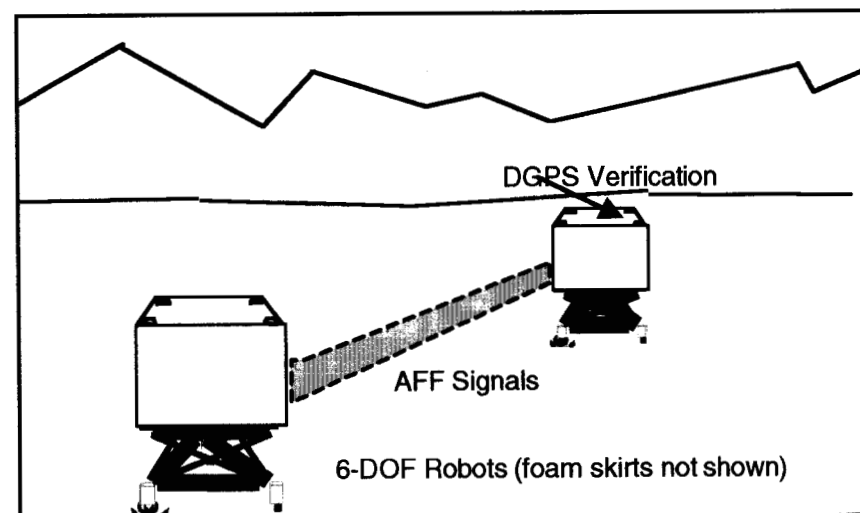
3-DOF Large Scale FF Testbed



**3-DOF Precision Coordinated
Attitude Testbed**



- End-to-end formation flying performance demonstration
 - Closed-loop demo between H/W & S/W
 - Large scale demo
- Testbed facility & description
 - 6-DOF wheeled robots with accurate S/C models



6-DOF Large Scale FF Testbed



Visions for the Future



- Autonomous constellation control & operations
- Autonomous fleet control & operations

